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POLARIZATION TRANSFORMER AND POLARIZATION MODE DISPERSION COMPENSATOR

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Field of the Invention

[01] The present invention relates in general to the field of polarization transformation of light and, more particularly, to polarization transformation of optical signals exhibiting polarization mode dispersion.

BACKGROUND OF THE INVENTION

[02] Single-mode optical fiber is used in a variety of telecommunications systems. Despite its name, single-mode optical fiber actually transmits light in two distinct polarization modes. In a perfectly symmetrical single-mode optical fiber, these two modes travel through the fiber in exactly the same manner and are otherwise indistinguishable. However, imperfections in the fiber, either created during manufacture or caused by some external force on the fiber, can cause the refractive index of the glass core to differ slightly for light in the two different polarization modes, an effect called birefringence.

[03] Birefringence associated with an optical fiber will cause the light in the two different polarization modes to travel at differing speeds. The birefringence encountered can be both uniform (e.g., a uniform manufacturing defect) and random. If the light traveling down the fiber is a typical optical pulse train used for telecommunications, each pulse initially might have components in both polarization modes. After traveling a distance down the fiber the two polarization components of the pulses will be separated in time. This time separation is called differential group delay. The statistical accumulation of differential group delay due to random polarization shifts and distribution of birefringence in the optical fiber is known as polarization mode dispersion (PMD). If it is too great, PMD causes the pulses to

spread out thereby making it difficult to resolve individual pulses and thus transmit data without introducing transmission errors.

[04] Polarization mode dispersion occurs in an optical fiber as a result of a small residual birefringence that is introduced in the fiber core by asymmetric internal stress or strain as well as random polarization coupling due to external forces acting upon the fiber. Thus, polarization mode dispersion may severely impair the transmission of a signal in an optical fiber network. It is well known that polarization mode dispersion has different effects on certain polarization components of an optical signal propagating through an optical fiber transmission line, such that differential time delays occur among the components as they travel through the fiber. These differential time delays can range from about 0.1 ps/(km)$^{1/2}$ for low-PMD optical fibers of recent manufacture to several ps/(km)$^{1/2}$ for single-mode optical fibers of older manufacture. For long-distance optical fiber links, e.g., a 100 km terrestrial transmission system using single-mode fiber, the differential time delay that can result from polarization mode dispersion may be more than 20 ps. Large time delays occurring between different polarization components can cause significant broadening of the optical pulses propagating through an optical link. This is a particular problem in digital lightwave systems operating at bit periods comparable to PMD, e.g., at least 10 Gbps per transmitted-wavelength-channel.

[05] If the birefringence causing polarization mode dispersion were stable over time, it would be relatively simple to correct for the problem. However, random or time-varying mechanical stress on the deployed fiber leads to unpredictable polarization mode dispersion. Similarly, dynamic environmental changes result in polarization mode dispersion changes that can last for variable periods of time and vary with wavelength. In addition to diurnal heating and cooling, even faster thermal and mechanical effects, such as vibration from passing vehicles, fiber movement in aerial spans, and cabling disturbances by workers can cause polarization mode dispersion that possesses even greater variability. The rapid variation of these effects (e.g., on the order of a fraction of a millisecond to tens of seconds) suggests the need for relatively rapid corrective systems to preserve the integrity and lower the error rate of the optical data transmission. Moreover, the unpredictable nature of the resulting

polarizations suggests the need for corrective systems that can adapt to a wide range of changes in birefringence.

[06] Most devices that are intended to mitigate the problems of PMD do so by applying an appropriate delay to the faster of the two polarization components that make up the PMD degraded optical pulses. To do so, these devices should continuously and rapidly transform the state of polarization of these two polarization components to a known state, thereby controlling the polarization states. Continuously adjustable or "endless" polarization transformers provide continuous control of the polarization state for a wide range of input polarizations. The simplest example is a rotatable wave plate. Unfortunately, most devices of this nature have relatively slow response times (perhaps on the order of tens or hundreds of milliseconds), and so they are not the most desirable devices to use to correct for polarization mode dispersion. A variety of devices with faster response times are available, but these devices generally have a limited range through which they can transform a polarization state and require resetting once they have reached their limit. Reset cycles can give rise to periods of unacceptable loss in overall system performance. In addition, multiple limited-range devices need to be combined in series, each device having a polarization transformation range that covers a range different from, but possibly overlapping with, the other devices. Such stacks of devices can still suffer from problems associated with reset cycles, as well as increased complexity and signal loss.

[07] Accordingly, it is desirable to have polarization transforming devices, and particularly polarization transforming devices for use in polarization mode dispersion compensators, that have adequate response time and solve or alleviate the other problems of prior art devices.

SUMMARY OF THE INVENTION

[08] It has been discovered that a polarization transformer can be constructed using a continuously adjustable polarization transforming device and a limited-range adjustable polarization transforming device. In general, the response time of the limited-range adjustable polarization transforming device is faster than that of the continuously adjustable polarization transforming device. When the two devices are

properly controlled using error signals derived from a transformed optical signal, the polarization state of the optical signal can be adjusted with sufficient speed and without the loss of control associated with reset cycles.

[09] Accordingly, one aspect of the present invention provides a polarization transformer operable to reorient polarization components of an incident optical signal. The polarization transformer includes a continuously adjustable retarder and a limited-range adjustable retarder. The continuously adjustable retarder is operable to provide reset-free operation and continuous control of a polarization state of the optical signal. The limited-range adjustable retarder is located in optical communication with the continuously adjustable retarder and is operable to provide limited-range control of the polarization state of the optical signal.

[10] Another aspect of the present invention provides a system for compensating for polarization mode dispersion in an optical signal. The system includes a polarization transformer, a delay system, and a controller. The polarization transformer is operable to reorient polarization components of an incident optical signal and includes a continuously adjustable retarder and a limited-range adjustable retarder. The continuously adjustable retarder is operable to provide reset-free operation and continuous control of a polarization state of the optical signal. The limited-range adjustable retarder is located in optical communication with the continuously adjustable retarder and is operable to provide limited-range control of the polarization state of the optical signal. The delay system is operable to adjust the relative delay between a first reoriented polarization component of the optical signal and a second reoriented polarization component of the optical signal. The controller is coupled to the polarization transformer and is operable to provide control signals to the limited-range adjustable retarder and the continuously adjustable retarder.

[11] These and other aspects of the invention have numerous advantages. For example, the present invention provides a polarization controller having fewer devices that need to be controlled. This is particularly useful since each device may need to be controlled individually by phase sensitive detection, and thus additional frequencies would need to be reserved in the network for dithering. Also, by decreasing the number of devices used in polarization transformation, lower insertion losses are achieved.

[12] The foregoing is a summary and thus contains, by necessity, simplifications, generalizations and omissions of detail; consequently, those skilled in the art will appreciate that the summary is illustrative only and is not intended to be in any way limiting. As will also be apparent to one of skill in the art, the operations disclosed herein may be implemented in a number of ways, and such changes and modifications may be made without departing from this invention and its broader aspects. Other aspects, inventive features, and advantages of the present invention, as defined solely by the claims, will become apparent in the non-limiting detailed description set forth below.

BRIEF DESCRIPTION OF THE DRAWINGS

[13] A more complete understanding of the present invention and advantages thereof may be acquired by referring to the following description and the accompanying drawings, in which like reference numbers indicate like features.

[14] **Figure 1** illustrates a block diagram of a polarization transformer including a continuously adjustable retarder and a limited-range adjustable retarder.

[15] **Figure 2** illustrates one implementation of the polarization transformer of **Figure 1**.

[16] **Figure 3** illustrates a block diagram of a polarization mode dispersion compensator.

[17] **Figure 4** illustrates a block diagram of the polarization transformer controller shown in **Figure 3**.

DETAILED DESCRIPTION

[18] The following sets forth a detailed description of at least the best contemplated mode for carrying out the one or more devices and/or processes described herein. The description is intended to be illustrative and should not be taken to be limiting.

[19] The simplest polarization transforming devices typically include one or more optical elements known as retarders. The axes of the material exhibit different refractive index characteristics and are generally referred to as the fast (low index)

and slow (high index) axes. Orthogonal polarization components of light that enter a retarder will experience a relative phase shift upon output. This phase shift is generally dependent upon the thickness of the retarding medium and the degree of difference between the refractive indices of the fast and slow axes called birefringence of the retarding medium. Throughout this application, basic polarization transforming devices will typically be referred to as retarders, as is well known to those having ordinary skill in the art.

[20] **Figure 1** illustrates a block diagram of a polarization transformer **100** including a continuously adjustable retarder **110** and a limited-range adjustable retarder **120**. Input optical signal **130**, having a generally arbitrary polarization, is incident upon polarization transformer **100**. Input optical signal **130** is typically an optical communications signal of the sort transmitted on optical fibers. However, the operation of polarization transformer **100** can be understood with respect to any polarized light source and in particular any coherent polarized light source.

[21] Input optical signal **130** passes through continuously adjustable retarder **110** where its polarization is transformed based on the type of device used as continuously adjustable retarder **110** and any control signals applied to continuously adjustable retarder **110**. For example, if continuously adjustable retarder **110** is a rotatable half-wave plate coupled to a motorized mount, control signals can be applied to the motorized mount to cause the half-wave plate to be rotated by a desired amount, thereby effecting a desired polarization transformation. Continuously adjustable retarder **110** is continuously adjustable or "endless" in that it provides continuous control of the polarization state over a virtually infinite range of input polarization. Continuously adjustable retarder **110** does not require resetting, with the associated undesirable reset cycle, because the range through which it can adjust polarization is not limited. In addition to conventional wave plates, a variety of different continuously adjustable retarders or combinations of retarders, as is well known to those having ordinary skill in the art, can be used to implement continuously adjustable retarder **110**. For example, continuously adjustable retarder **110** can be constructed from lithium niobate devices, semiconductor devices, and liquid crystal devices such as vertically-aligned nematic liquid crystal cells using variable lateral electric fields.

[22] The transformed optical signal passes from continuously adjustable retarder **110** to limited-range adjustable retarder **120**. Note that in the example of **Figure 1**, the order of polarization transforming devices is continuously adjustable retarder **110** first, and then limited-range adjustable retarder **120**. This particular order need not be the case. For example, limited-range adjustable retarder **120** and continuously adjustable retarder **110** can be located with respect to each other such that the optical signal passes through limited-range adjustable retarder **120** first. Alternately, components of both continuously adjustable retarder **110** and limited-range adjustable retarder **120** can be intermingled so that the optical signal does not necessarily pass through one or the other first.

[23] Limited-range adjustable retarder **120** is typically constructed from one or more retarders that have a limited range of polarization transformation but whose response time is shorter than that of continuously adjustable retarder **110**. A variety of different technologies can be used to construct limited-range adjustable retarder **120** including: liquid crystal cells, lithium niobate crystals, lanthanum modified lead zirconate titanate (PLZT) materials, and mechanically or thermally stressed optical fiber. In general, any material or device exhibiting some degree of tunable birefringence and an adequate response time can be used for limited-range adjustable retarder **120**. In some cases, for example liquid crystal cells, multiple devices may be combined to form limited-range adjustable retarder **120**. In such cases the number of devices needed is typically less than would be needed if a continuously adjustable device were to be formed, thereby reducing the complexity and signal loss associated with the device.

[24] Output optical signal **140** is the product of polarization transformation caused by both continuously adjustable retarder **110** and limited-range adjustable retarder **120**. Output optical signal **140** possesses the desired polarization state based on control signals applied to polarization transformer **100**. In many uses of polarization transformer **100**, it will be desirable to configure the transformer to produce an output optical signal **140** having a specified output polarization regardless of the polarization of input optical signal **130**. The combination of continuously adjustable retarder **110** and limited-range adjustable retarder **120** allows polarization transformer **100** to quickly respond to changes in the polarization state of input optical signal **130**. In

general, the overall response time of polarization transformer **100** will be approximately the same as that of the limited-range adjustable retarder **120** so long as continuously adjustable retarder **110** is fast enough to compensate for desired changes in polarization state that are outside the range of the devices used for limited-range adjustable retarder **120**.

[25] **Figure 2** illustrates one implementation of a polarization transformer **200**. Liquid crystal half-wave retarders **210** and **230** are located on either side of fixed quarter-wave plate **220**. Together, retarders **210**, **220**, and **230** form a limited-range adjustable retarder. In a typical implementation, each of liquid crystal retarders **210** and **230** is formed from one or more liquid crystal cells. A liquid crystal cell is usually constructed from a layer of liquid crystal material sandwiched between two transparent, or substantially transparent, windows. The windows are typically composed of a transparent substrate such as fused silica. Transparent electrically conductive electrodes, e.g., a one or more indium tin oxide (ITO) layers, can also be formed on the transparent substrate. The window must be sufficiently transparent at the wavelength of the optical signal so that there is not too much signal loss as the optical signal passes through the cell. The electrodes are present so that an appropriate controlling voltage can be applied to tune the cell, thereby adjusting the polarization of light passing through the cell. Alternately, a liquid crystal retarder can be formed from several liquid crystal cells, each having electrodes used to apply the tuning voltage. In one particular example, liquid crystal retarders **210** and **230** are each formed from three liquid crystal cells positioned in series. Two of the liquid crystal cells rotate the optical signal's polarization in one direction when an increasing voltage is applied, while the third liquid crystal cell rotates the optical signal's polarization in the opposite direction as the increasing voltage is applied. A variety of different liquid crystal materials can be used in liquid crystal retarders **210** and **230**, including so-called analog liquid crystals based on nematic liquid crystal (NLC), ferroelectric liquid crystal (FLC), and fluorinated ferroelectric liquid crystal (fFLC) materials. Examples of fluorinated ferroelectric liquid crystal materials can be found in the U.S. Patent 6,309,561 entitled "Liquid Crystal Compounds Having a Chiral Fluorinated Terminal Portion," naming Hasegawa et al. as inventors, which is hereby incorporated by reference herein in its entirety.

[26] Operation of the limited-range adjustable retarder formed by retarders **210**, **220**, and **230** can better be understood by making reference to the polarization state representation using the Poincare sphere, as will be known to those having ordinary skill in the art. Polarization states can be represented as points on the Poincare sphere, and this representation is fully described in published literature, e.g. Rashleigh: "Origins and Control of Polarisation Effects in Single Mode Fibres", J Lightwave Technology Vol. LT 1 No 2 June 1983 p. 312-331. Any general elliptical polarization state is represented on the sphere by a single point S, and all possible polarization states lie on the sphere. Birefringence causes a change in polarization state from S to some other point on the sphere S' and thus a rotation about an axis passing through the center of the sphere, through an angle which depends on the magnitude of the birefringence. Consequently, transforming one arbitrary polarization state to another arbitrary polarization state requires rotations about two separate axes. Retarders **210** and **230** accomplish these separate rotations. However, in order for the rotations to be about two orthogonal axes for the example given here of two half-wave retarders **210** and **230**, a 90° phase shift must be introduced by quarter-wave plate **220**.

[27] Rotatable half-wave plate **240** is used to implement the continuously adjustable retarder. As previously noted, such wave plates can be mounted on motorized rotation mounts or stages such that the wave plate can be continuously rotated. For example, such motorized rotation mounts can be controlled with positive and negative voltages to rotate the wave plate clockwise and counter-clockwise respectively. Because of the design of the limited-range adjustable retarder formed by retarders **210**, **220**, and **230**, only a single rotatable half-wave plate **240** is used to implement the continuously adjustable retarder. However, in other designs the continuously adjustable retarder can include multiple wave plates and/or wave plates providing different amounts of retardation. Other types of retarders can be used in place of rotatable half-wave plate **240**, including certain liquid crystal retarders (e.g., vertically-aligned nematic liquid crystal cells using variable lateral electric fields), birefringent crystals (e.g., lithium niobate devices), and semiconductor devices.

[28] In general, those having ordinary skill in the art will readily recognize that a variety of different polarization transforming devices can be used to implement the aforementioned continuously adjustable and limited-range adjustable retarders.

[29] Although not shown in conjunction with **Figure 2**, controller(s) for both continuously adjustable and limited-range adjustable retarders are responsible for adjusting the retarders to produced the desired output polarization. In another example of polarization transformer **200**, half-wave plate **240** is placed before retarders **210**, **220** and **230**, i.e., the optical signal passes through half-wave plate **240** first. In this implementation, one controller, or section of a larger controller, is used to adjust the polarization transformation caused by liquid crystal retarders **210** and **230**. Another controller, or section of a larger controller, adjusts the setting of rotatable half-wave plate **240** in order to try to center the liquid crystal retarders **210** and **230** in their range of tunability. Thus, liquid crystal retarders **210** and **230** attempt to maintain the desired output polarization while the polarization of the signal received by the limited-range adjustable retarder is now governed by a combination of the original polarization of the input optical signal and the continuously adjustable retarder. Thus, the limited-range adjustable retarder formed from retarders **210, 220** and **230** need only compensate for the difference between the polarization as adjusted by rotatable half-wave plate **240** and the desired output polarization.

[30] **Figure 3** illustrates a block diagram of polarization mode dispersion compensator **300**. Polarization mode dispersion compensator **300** serves to reverse the pulse broadening effects that arise as an optical signal travels through, for example, single-mode optical fiber **360**. In general, polarization mode dispersion compensator **300** transforms the polarization state of the optical signal arriving from single-mode optical fiber **360** into a known polarization state so that the transformed optical signal can be sent through a delay system to adjust the phase difference between polarization components of the optical signal causing the polarization mode dispersion. As illustrated, polarization mode dispersion compensator **300** includes polarization transformer **310**, delay system **320**, and controller **350**. Polarization mode dispersion compensator **300** can also include other devices such as optical tap **330** and detector **340**, or alternately, these devices (or their equivalents) can be part of the optical network in which polarization mode dispersion compensator **300** is used.

[31] Once the optical signal exhibiting polarization mode dispersion is received from single-mode optical fiber **360**, which is, for example, part of a telecommunications network, the optical signal is received by polarization transformer **310**. Polarization transformer **310** includes both continuously adjustable and limited-range adjustable retarders, and thus the aforementioned polarization transformers **100** and **200** serve as examples of polarization transformer **310**. Once the polarization state of the optical signal is transformed into a desired polarization state, the signal is received by delay system **320**.

[32] In one example, delay system **320** is a known-length span of polarization maintaining optical fiber. Polarization maintaining optical fiber has an internal strain or asymmetry causing the fiber to have a well-defined birefringence. When properly oriented so that the polarization components of the optical signal emerging from polarization transformer **310** coincide with the slow and fast axes (as appropriate) of the polarization maintaining optical fiber, the polarization maintaining optical fiber will delay one polarization component of the optical signal with respect to the other. The amount of delay introduced, and thus the degree to which the two polarization components are brought back into phase with each other, will generally depend on the length of the polarization maintaining optical fiber. Accordingly, it is important that polarization transformer **310** be able to transform the polarization of the optical signal in a manner appropriate for delay system **320**.

[33] Other examples of suitable devices, both fixed and variable, for use as delay system **320** are well known in the art. For example, variable delay elements include: optical fibers that are either squeezed or heated to alter propagation characteristics, systems including a series of optical switches connected in stages by different incremental lengths of optical fiber, and other tunable fiber delay lines. Such variable delay elements typically require control systems which would be included as part of delay system **320**.

[34] If the signal level of the optical signal is sufficiently high, or if polarization mode dispersion compensator **300** is inserted into a system at a point where signal loss is not critical, filtering devices can be used in place of delay system **320** to filter out one polarization component of the optical signal, thereby reducing or eliminating the effect of polarization mode dispersion. For example, a single-polarization optical

fiber (an optical fiber in which one polarization component is significantly attenuated) could be used to filter the optical signal. Other devices useful for this purpose, such as filters and polarizing beamsplitters, are well known to those having ordinary skill in the art.

[35] Once the effects of polarization mode dispersion have been compensated for, the optical signal is generally passed on to the next element of the communications network.

[36] Input for controller **350** may be in the form of information about the state or degree of polarization of the input optical signal. Alternatively, this input may be in the form of an error signal supplied by the other network components or derived from light that is sampled after polarization transformer **310**, or after delay system **320**.

[37] In one embodiment of the feedback and control system for polarization mode dispersion compensator **300**, a portion of the optical signal is split off or sampled by optical tap.**330**. Optical tap **330** generally includes one or more beamsplitters that pass a portion of the optical signal to detector **340.** Detector **340** uses one or more photodetctors and associated error signal circuitry to convert the optical signal into one or more error signals for use by controller **350**.

[38] Controller **350** uses the input signals to determine control signals that are sent to polarization transformer **310**. The input signals received can be amplified, filtered, or processed in any other way necessary to produce appropriate control signals for polarization transformer **310**. Moreover, controller **350** can include one or more separate controllers for the various retarding elements included in polarization transformer **310**. The control signals are used to adjust the various retarders in polarization transformer **310**, thereby producing the desired polarization transformation. In one example, the controller adjusts the polarization transformation induced by polarization transformer **310** so as to minimize the error signal received from detector **340** and thus maximize the strength of the optical signal emerging from delay system **320**. Various types of controller devices and feedback schemes will be known and understood by those of ordinary skill in the art.

[39] **Figure 4** illustrates a block diagram of one embodiment of controller **350**. In this example, controller **350** is designed to provide control signals to a polarization transformer such as polarization transformer **200** illustrated in **Figure 2**. As in **Figure 3**, detector **340** generates one or more error signals based on the portion of the optical signal sampled by optical tap 330. Photodetector **341** and error signal circuit **343** provide an error signal based on the detected optical signal. The error signal is sent to lock-in amplifiers **351A** and **351B** which amplify the error signal and separate it from other noise in the signal. Each of lock-in amplifiers **351A** and **351B** utilize a reference signal generated by oscillator **353**. As is well known in the art, oscillator **353** can be a standalone function generator, a reference source internal to the lock-in amplifiers, or any other appropriate reference signal generator. Lock-in amplifiers **351A** and **351B** can utilize the same reference signal, reference signals differing only by a phase shift, or different reference signals. Feedback circuits **355A** and **355B** further process the error signals amplified by lock-in amplifiers **351A** and **351B**. For example, feedback circuits **355A** and **355B** can implement one or more of proportional, integral, and derivative (PID) control actions. The output signals from feedback circuits **355A** and **355B** are then used to control voltage sources (**357A** and **357B**) that supply control voltages to, for example, liquid crystal retarders **230** and **210**. In one example, voltage sources **357A** and **357B** are simple transformer circuits as illustrated.

[40] In operation, each of the liquid crystal retarders **230** and **210** are dithered about a set voltage. The oscillation frequencies can be up to hundreds kHz, generally depending on the response of the liquid crystal retarders **230** and **210** and the presence of other frequency signals in the overall system. Liquid crystal retarders **230** and **210** can each be dithered about the same frequency or different frequencies as appropriate. In an example where both retarders **230** and **210** are dithered about the same frequency, a 90° phase shift can be introduced between the two reference signals for proper phase detection. In phase variation in the error signals are detected by lock-in amplifiers **351A** and **351B** and developed by feedback circuits **355A** and **355B**. Exemplary parameters for this system include: 4 ms to 1 s integration times, 0.05 to 0.8 V dithering voltages, and 2 kHz dithering frequency. Other control schemes and parameters will be well known to those having ordinary skill in the art. For example, one lock-in amplifier can be used particularly if the same dithering frequencies

(subject to an appropriate phase shift) are used for liquid crystal retarders **230** and **210**.

[41] In the configuration illustrated in **Figure 4**, the continuously adjustable retarder (e.g., half-wave plate **240**) is controlled by a signal based on the output of feedback circuits **355A** and **355B** and further developed by continuously adjustable retarder error circuit **359**. For example, if rotatable half-wave plate **240** uses a motorized rotation mount, circuit **359** can use the output of one or both of feedback circuits **355A** and **355B** to produce a motor control signal that will rotate wave plate **240** in a direction where liquid crystal retarder **210** maximizes the detected signal. Ultimately, this will cause the control voltage applied liquid crystal retarder **210** to either decrease or return to a value representative of the center point of the retarder's tuning range. Thus, continuously adjustable retarder error circuit **359** may have to scale received signals to values appropriate for controlling retarder **240**. In another example, continuously adjustable retarder error circuit **359** generates an error signal based on the voltage values for both liquid crystal retarders **230** and **210**. Such an error signal can be determined by or proportional to the sum of the squares of the two voltage values. Other control schemes will be understood by those having ordinary skill in the art.

[42] Although the present invention has been described with respect to a specific preferred embodiment thereof, various changes and modifications may be suggested to one skilled in the art and it is intended that the present invention encompass such changes and modifications within the scope of the appended claims.